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Age-related changes in mechanical and metabolic energy during typical gait

P. Van de Walle [a,b,c,*], K. Desloovere [b,c], S. Truijen [a], R. Gosselink [c], P. Aerts [d,e], A. Hallemans [a,d]

[a] Department of Health Care, Artesis University College of Antwerp, Belgium
[b] Clinical Motion Analysis Laboratory, CERM, University Hospital Pellenberg, Belgium
[c] Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, Katholieke Universiteit Leuven, Belgium
[d] Department of Biology, Functional Morphology, University of Antwerp, Belgium
[e] Department of Movement and Sports Sciences, Ghent University, Belgium

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ABSTRACT

The purpose of the study was to investigate and report age-related changes in walking energy expenditure using different methods of energy estimation. For 81 children and 16 adults (3–35 years) energy expenditure was investigated by using the following methods: analysis of energy changes of the centre of body mass (external and internal mechanical work), sum of segmental energies, sum of net joint work and gross and net metabolic cost, as well as net non-dimensional oxygen cost.

Different methods of energy estimation not only show different outcome results but also different age-related changes. Significant changes were found for negative net joint work, external mechanical work and recovery as well as sum of segmental energies, until 9, 11 and 19 years respectively. Positive net joint work showed no differences between age groups and the differences for internal work did not suggest development.

Metabolic energy showed significant changes until adult age. Gross cost decreases with increasing age in children and, although more gradually, still in adolescents. Net and net non-dimensional cost shows a more constant decrease with increasing age until adulthood.

Therefore, the choice of estimation method and the use of age-related reference data when evaluating young patients should be carefully considered. For interpretation of oxygen consumption in children the use of net is superior to gross cost, but even after net non-dimensional normalization, age-related reference data should be used.

1. Introduction

Human walking is very efficient but age or pathology related changes in the gait pattern can lead to significant increases in energy expenditure during walking (EE_{walk}). EE_{walk} can be characterised in two different ways: mechanical energy (E_{mech}) estimations [1–3] or metabolic energy (E_{met}) measurements [4,5].

E_{mech} is generally estimated by one of three approaches: (1) analysis of energy changes of the centre of mass of the whole body (CoM) relative to the surroundings (external work, W_{ext}) and of the body segments relative to the CoM (internal work, $W_{int,k}$) [1,2,6,7]; (2) analysis of the energy changes of moving body segments (sum of segmental energies, W_{SSE}) or (3) measurement of muscle power around the joints (net joint work, W_j) [8]. These three approaches can provide different clinical information e.g. where the CoM approach does not take into account negative work at all, in W_{SSE} it is accounted for and W_j even provides a separate outcome for positive and negative work. In all E_{mech} estimations the actual amount of work performed is underestimated as additional metabolic work resulting from isometric muscle contractions or antagonist co-contractions is not taken into account [8]. The problem of underestimation is overcome when assessing E_{met} i.e. measuring oxygen consumption (O_2-consumption) during walking [5]. The clinical drawback of E_{met}, however, is that one can only detect an increased EE_{walk}, without any indication about what causes it. It also remains unclear which E_{met} parameter ideally should be used. Net cost (gross – resting utilization) provides a more direct indication of walking efficiency but is less reproducible than gross cost [9]. On the other hand Thomas et al. could not find any significant advantage of using one E_{met} measurement over another [10].

EE_{walk} is different for children as compared to adults as they differ in kinematics, kinetics and muscle activation patterns [11–14].

The increased E_{mech} is well studied at the onset of walking [12,13,15]. In 2-year old children, W_{ext} at self-selected walking

* Corresponding author at: Clinical Motion Analysis Laboratory, University Hospital Pellenberg, Weligerveld 1, 3212 Pellenberg, Belgium. Tel.: +32 16 33 80 13; fax: +32 16 33 80 12.
E-mail address: patricia.vandewalle@artesis.be (P. Van de Walle).

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speed (WS_{ss}) is 2–3 times greater than in adults and abrupt decreases are observed from 1–2 to 3–4 years [13]. After the age of four the decrease in mass-specific W_{ext} is more gradual [11,13,14]. The energy saving inverted pendulum mechanism is not present at the onset of independent walking but has to be learned from experience [12,13,15]. Mass-specific W_{ext}, $W_{int,k}$ and total mechanical work ($W_{tot} = W_{int,k} + W_{ext}$) per stride are similar across children of different ages walking at a similar speed but expressed per meter (mechanical cost) they are greater in children until the age of 10 and above speeds of $\sim$1 m s^{-1} [14].

E_{met} increases by increasing age [16–20]. In young children (3–6 years) gross oxygen cost (ml kg^{-1} m^{-1}) is 70% higher than in adults. The difference is only 15% in 9–10-year olds and seems to have disappeared by the age of 12 [18,21], although other authors still report significant differences between adolescents and adults [16,20]. Recently Schwartz et al. proposed a new normalization scheme for E_{met} that allows elimination of changes due to the different body dimensions of children and adults which can be invaluable in studying age-related changes [22].

It is not yet clear at which age different parameters of EE_{walk} can be considered mature. However, in a clinical setting the knowledge of changes in EE_{walk} being age or pathology related is crucial. Research on E_{mech} mainly focuses on the onset of walking [12–15] and to the best of our knowledge the age-related changes of W_{SSE} and W_j are, to date, not documented. Changes of E_{met} with age are better documented but not always with recent technology and normalization schemes.

Therefore, the aim of this study was to investigate changes in EE_{walk} in a large group of children from 3 years up to adulthood. As the advantage of one estimation method over another remains unclear, different methods of calculating E_{mech} and E_{met} were compared.

2. Materials and methods

Between 2003 and 2008, 108 children and adults with a typical gait pattern, recruited from family and friends of colleagues and patients, underwent gait analysis (GA) and measurement of O_2-consumption in random order. Exclusion criteria were orthopaedic, neurological or cardiovascular pathologies or diagnosis of maturational problems. The study was approved by local ethical committee.

During GA total body kinematics and kinetics were collected while barefoot walking on a 10-m walkway at WS_{SS} using an eight-camera VICON System (Mx camera-workstation, 120 Hz, PlugInGait marker set, VICON, Oxford Metrics, Oxford, UK) and two embedded force plates (0.4 m $\times$ 0.5 m, 1500 Hz, Advanced Mechanical Technology Inc., Watertown, MA).

O_2-consumption was measured breath by breath during a 5 min rest period (sitting on a chair), 3 min of standing and 8 min of walking with shoes at WS_{SS} on a figure eight track (34 m) with K4b2 (Cosmed, Rome, Italy). No strict instructions on food intake were given but testing took place >2–3 h after a meal [23].

GA data were excluded when a participant's spontaneous step length did not allow separate registration of force data under the left and right foot (no valid kinetics). O_2-consumption was not measured when the combination of the two tests was too demanding and during a period where the K4b2-device was unavailable. For 55 children and 15 adults a complete dataset was available, for 27 participants either only valid kinetics (14 children) or valid O_2-consumption measurement (12 children, one adult) were available and 11 subjects (five children, six adults) were excluded because valid kinetics and O_2-consumption measurement were not available. The remaining 97 subjects were divided into five age groups: young children, G1 (3–5 years); children, G2 (6–9 years); pubertal children, G3 (10–13 years); adolescents, G4 (14–17 years) and adults, G5 (20–35 years). Group mean and standard deviation of anthropometrics are presented in Table 1.

2.1.1. Data analysis

For GA up to three trials per subject were analysed. Only strides at least two steps after gait initiation were used for analysis. When measuring ground reaction forces (GRF) of both legs over one gait cycle with only two force plates, GRF of the contra-lateral leg is not available during first phase of double support. This missing part was completed with GRF data from the contra-lateral leg at the beginning of the next gait cycle.

Positive external mechanical work and percentage of recovered energy (recovery, R) were computed according to Cavagna [24].

Potential (E_{pot}) and kinetic (E_{kin}) energy changes of the CoM were calculated (Appendix A, Eqs. (A1) and (A2)). Total E_{mech} was obtained by summing E_{pot} and E_{kin} instant by instant. The amount of positive work performed on the CoM (W_{ext}) equals the positive increments in total E_{mech} over an integral number of steps. R was calculated as a measure of the pendulum like transfer between E_{kin} and E_{pot} (Appendix A, Eq. (A3)) [7].

$W_{int,k}$ was calculated by summing the positive increments in E_{kin} changes of the body segments which were determined by a 12-segment model, based on anthropometrical data from Dempster (>14 years) [25] and Jensen (<14 years) [26]. Translational and rotational energy of the segments were summed (see [12]). W_{tot} can then be obtained by summing W_{ext} and $W_{int,k}$.

To obtain W_{SSE}, segmental energies were determined and summed at each instant (Appendix B).

W_j was obtained by separate integration of positive and negative net joint power profiles (J kg^{-1} s^{-1}) for neck, shoulders, elbows, wrists, waist, hips, knees and ankles as obtained from the Vicon Plug-in-Gait model. Subsequently positive and negative work performed at each joint was separately summed for all joints (J kg^{-1} m^{-1}). The addition of the sum of respectively positive and negative net joint work of all joints respectively gave the positive and negative net joint work of the whole body (W_j^+ and W_j^-).

Average O_2-consumption and respiratory exchange ratio (RER) were calculated at rest (2 min) and during walking (3 min) during a steady state period (no visual decrease or increase in O_2-consumption). The first 3 min of resting/walking were excluded from the analysis in order to allow the subjects to reach steady state. Walking speed was calculated as the mean speed during the steady state period of walking. For comparison with E_{mech} parameters, O_2-consumption was expressed in J kg^{-1} [27]:

$$(4.960 \times \text{RER} + 16.040) \times \text{VO}_2 \quad (1)$$

Net O_2-consumption was then obtained by subtracting O_2-consumption at rest from O_2-consumption during walking (gross O_2-consumption). O_2-cost (J kg^{-1} m^{-1}) was calculated by dividing O_2-consumption by walking speed. O_2-cost was also expressed non-dimensional ($cost_{nn}$) according to the non-dimensional normalization scheme by Schwartz et al. (Appendix C) [22].

2.1.2. Statistical analysis

Statistical analysis was performed with SPSS (version 12.0, SPSS Inc.). All data were normalized to body mass and stride length (J kg^{-1} m^{-1}). Trials were rejected according to Cavagna et al. when $R \leq 10\%$ [7] and data were carefully checked for extreme values per age group and per parameter to check for integration errors in GRF by using data of the beginning of the next gait cycle. Therefore, eight trials for W_{ext} and R and three trials of W_j were rejected. Data were tested for normal distribution by Kolmogorov–Smirnov test. A General Linear Model (GLM) was performed with age group as a fixed factor. Due to missing data (no valid kinetics or upper body kinematics, rejected trials) the number of valid trials differed per subject. This was accounted for by including individual in the model as random factor. Main and possible interaction effects were considered. It is well known that walking speed largely affects energy expenditure during walking. Whenever a significant and meaningful correlation (Pearson correlation coefficient) was found between WS_{SS} and the energetic parameter of interest, WS_{SS} was also included in the GLM ($W_{int,k}$ and W_{tot}, $r = 0.415$–0.531, $p < 0.01$). Differences between age groups were investigated by pairwise post hoc comparisons (Tukey HSD) with significance level at $p < 0.05$.

If Tukey's test revealed significant differences between age groups for a specific energetic parameter, a linear regression analysis was performed between that energetic parameter and age. The goal was to determine at what age this parameter can be considered as mature. To do so, two new pools of subjects were created,

Table 1
Number of participants (male/female) per group; mean, range and standard deviation for age per group; mean and standard deviation per age group for height, body weight and body mass index (BMI).

	Group 1 3–5 years	Group 2 6–9 years	Group 3 10–13 years	Group 4 14–17 years	Group 5 adults
Subjects (male/female)	16 6/10	27 7/20	19 12/7	19 10/9	16 4/12
Age [years]	4.4 ± 0.96 [2.9–5.7]	7.9 ± 6.2 [6.2–9.5]	11.6 ± 1.1 [10.2–13.4]	16.1 ± 1.1 [14.0–18.0]	26.2 [20.9–35.2]
Height [m]	105.8 ± 8.1	129.0 ± 8.2	153.7 ± 7.6	172.7 ± 9.9	169.9 ± 6.5
Body weight [kg]	17.0 ± 2.7	25.7 ± 4.4	40.7 ± 7.2	61.1 ± 12.8	63.8 ± 6.7
BMI [kg m^{-2}]	15.5 ± 1.7	15.5 ± 1.2	17.1 ± 1.8	20.3 ± 2.8	22.1 ± 1.3

based on the results of the post hoc pairwise comparisons: an immature and a mature pool (cfr. Table 3A) Linear regressions with age were determined separately within the immature and mature pool. The intersection of both regression lines was considered as the estimated age of maturity (Table 3A). For regression analysis the different number of trials per individual were averaged and the mean was used.

3. Results

Mean and standard deviation of energy parameters and significant differences between age groups are presented in Table 2 and Fig. 1.

W_j^+ did not differ between age groups and for $W_{int,k}$ and W_{tot} the differences between the groups did not suggest development. Pearson correlation coefficient was calculated for $W_{int,k}$ and W_{tot} and confirmed that differences were not age-related ($r = -0.051$ to -0.159; $p = 0.119$–0.657).

Significant changes with age were found for W_j^-, W_{ext}, W_{SSE} and O_2-cost (Fig. 2 and Table 3). W_j^- was considered mature at 9 years followed by W_{ext} and recovery at 11 years. W_{SSE} values decreased up until 19 years. O_2-cost shows different developmental changes when using gross versus net O_2-cost. Both calculations, however, show significant decreases until adult age (all age groups together: gross cost: $r^2 = 0.47$; net cost: $r^2 = 0.20$; cost$_{nn}$: $r^2 = 0.20$, $p < 0.001$). In gross O_2-cost, however a rapid decrease in G1 − G3 was found, followed by a slower but continuous decrease in G4 − G5 (Fig. 2E).

4. Discussion

This study is the first to compare different methods to explore EE_{walk} in a large continuous age range from 3 years up to adult at WS_{SS}. The strength of this study lies in the fact that all energy parameters were calculated on the same population, on the same day and, moreover, for the mechanical estimations also during the same gait cycle. This allows straightforward comparison of the age when each aspect of EE_{walk} reaches adult-like values. Results indicate that different estimation methods of EE_{walk} have a different outcome as well as a different age when a parameter can be considered mature.

Various methods of E_{mech} estimation all highlight different aspects of total EE_{walk}. These differences can prove invaluable when investigating why EE_{walk} is increased in young children and patients. The differences between estimation methods are confirmed by the differences in magnitude of work (Table 2, Fig. 1). W_{tot} shows the lowest values, W_{SSE} the highest and the sum of W_j^+ and $|W_j^+|$ lies in between. This can be explained by the fact that in W_j and W_{SSE}, negative work is taken into account whereas W_{tot} only considers positive work. While parameters of E_{mech} only reflect specific biomechanical aspects of a gait pattern, measurements of E_{met} reflect the total energy produced including e.g. isometric contractions and co-contractions. This explains the higher values for net O_2-cost compared to W_{tot} and W_j. W_{SSE}, however is higher than net O_2-cost suggesting overestimation. The exact relation between the different energy parameters in a more homogeneous population will be the object of further research.

There is not only a difference in magnitude between the different E_{mech} estimations as well as between E_{mech} and E_{met}, but also a clear diversity in their relationship with age. W_{ext} decreases and recovery increases by increasing age until 11 years. This is in accordance with Schepens et al. who found W_{ext} to be higher in children than in adults at speeds above 1 m s^{-1} and for subjects younger than 10 years [14]. No age effect was found for $W_{int,k}$. The

Table 2
Mean and standard deviation of different energy parameters for all age groups and significant differences between the groups (post hoc Tukey). Note that the eldest groups do not always have the lowest values. Significant differences in energy parameters between age groups had an observed power of 0.76–1.00.

	Group 1 3–5 years	Group 2 6–9 years	Group 3 10–13 years	Group 4 14–17 years	Group 5 adults	Post hoc Tukey (p-value)
W_{ext} [J kg^{-1} m^{-1}]	0.53 ± 0.27 $n = 10$; $N = 5$	0.43 ± 0.10 $n = 46$; $N = 23$	0.34 ± 0.05 $n = 45$; $N = 18$	0.34 ± 0.07 $n = 39$; $N = 16$	0.35 ± 0.07 $n = 42$; $N = 15$	G1 − G2–5 ($p < 0.001$) G2 − G3–5 ($p < 0.001$)
Recovery [%]	44.0 ± 21.6 $n = 10$; $N = 5$	52.5 ± 7.0 $n = 46$; $N = 23$	59.3 ± 4.4 $n = 45$; $N = 18$	58.04 ± 8.5 $n = 39$; $N = 16$	58.05 ± 6.6 $n = 42$; $N = 15$	G1 − G2–5 ($p < 0.001$) G2 − G3–5 ($p < 0.001$)
$W_{int,k}$ [J kg^{-1} m^{-1}]	1.54 ± 0.32 $n = 48$; $N = 16$	1.47 ± 0.31 $n = 81$; $N = 27$	1.46 ± 0.19 $n = 57$; $N = 19$	1.37 ± 0.34 $n = 57$; $N = 19$	1.68 ± 0.27 $n = 48$; $N = 16$	G1 − G4 ($p = 0.021$) G2 − G5 ($p = 0.001$) G5 − G3–4 ($p \leq 0.001$)
W_{tot} [J kg^{-1} m^{-1}]	2.05 ± 0.55 $n = 10$; $N = 5$	1.82 ± 0.35 $n = 46$; $N = 23$	1.81 ± 0.19 $n = 45$; $N = 18$	1.62 ± 0.33 $n = 39$; $N = 16$	2.01 ± 0.30 $n = 42$; $N = 15$	G1 − G2–4 ($p \leq 0.002$) G2 − G4–5 ($p < 0.001$) G3 − G4–5 ($p < 0.001$) G4 − G5 ($p < 0.001$)
W_{SSE} [J kg^{-1} m^{-1}]	3.17 ± 0.65 $n = 48$; $N = 16$	2.97 ± 0.59 $n = 81$; $N = 27$	2.84 ± 0.39 $n = 56$; $N = 19$	2.43 ± 0.75 $n = 57$; $N = 19$	2.52 ± 0.59 $n = 48$; $N = 16$	G1 − G3–5 ($p \leq 0.040$) G2 − G4–5 ($p = 0.001$) G3 − G4 ($p = 0.003$)
W_j^+ [J kg^{-1} m^{-1}]	1.09 ± 0.11 $n = 12$; $N = 7$	1.13 ± 0.18 $n = 51$; $N = 22$	1.10 ± 0.17 $n = 50$; $N = 19$	1.13 ± 0.17 $n = 46$; $N = 17$	1.13 ± 0.20 $n = 45$; $N = 16$	–
W_j^- [J kg^{-1} m^{-1}]	-1.17 ± 0.27 $n = 12$; $N = 7$	-0.99 ± 0.13 $n = 51$; $N = 22$	-0.92 ± 0.17 $n = 50$; $N = 19$	-0.92 ± 0.19 $n = 46$; $N = 17$	-0.92 ± 0.20 $n = 45$; $N = 16$	G1 − G2–5 ($p < 0.001$) G2 − G3–5 ($p \leq 0.016$)
Net O_2-cost [J kg^{-1} m^{-1}]	2.75 ± 1.00 $N = 14$	3.36 ± 0.92 $N = 24$	2.68 ± 0.59 $N = 14$	2.57 ± 0.48 $N = 17$	1.99 ± 0.46 $N = 15$	G1 − G5 ($p = 0.055$) G2 − G4–5 ($p \leq 0.012$)
Gross O_2-cost [J kg^{-1} m^{-1}]	6.68 ± 1.90 $N = 14$	5.96 ± 1.49 $N = 24$	4.81 ± 0.95 $N = 14$	4.22 ± 0.52 $N = 17$	3.29 ± 0.49 $N = 15$	G1 − G3–5 ($p \leq 0.001$) G2 − G3–5 ($p \leq 0.040$) G3 − G5 ($p = 0.011$)
O_2-cost$_{nn}$	0.30 ± 0.13 $N = 14$	0.34 ± 0.09 $N = 24$	0.27 ± 0.06 $N = 14$	0.26 ± 0.05 $N = 17$	0.20 ± 0.05 $N = 15$	G1 − G5 ($p = 0.026$) G2 − G4–5 ($p \leq 0.015$)

n, number of trials per group used for analysis; N, number of patients per group used for analysis; W_{ext}, positive external work; $W_{int,k}$, positive internal work; W_{tot}, total positive work ($= W_{ext} + W_{int,k}$); W_{SSE}, work sum of segmental energies; W_j^+, positive joint work; W_j^-, negative joint work; net O_2-cost, net oxygen cost; gross O_2-cost, gross oxygen cost; O_2-cost$_{nn}$, net non-dimensional oxygen cost.

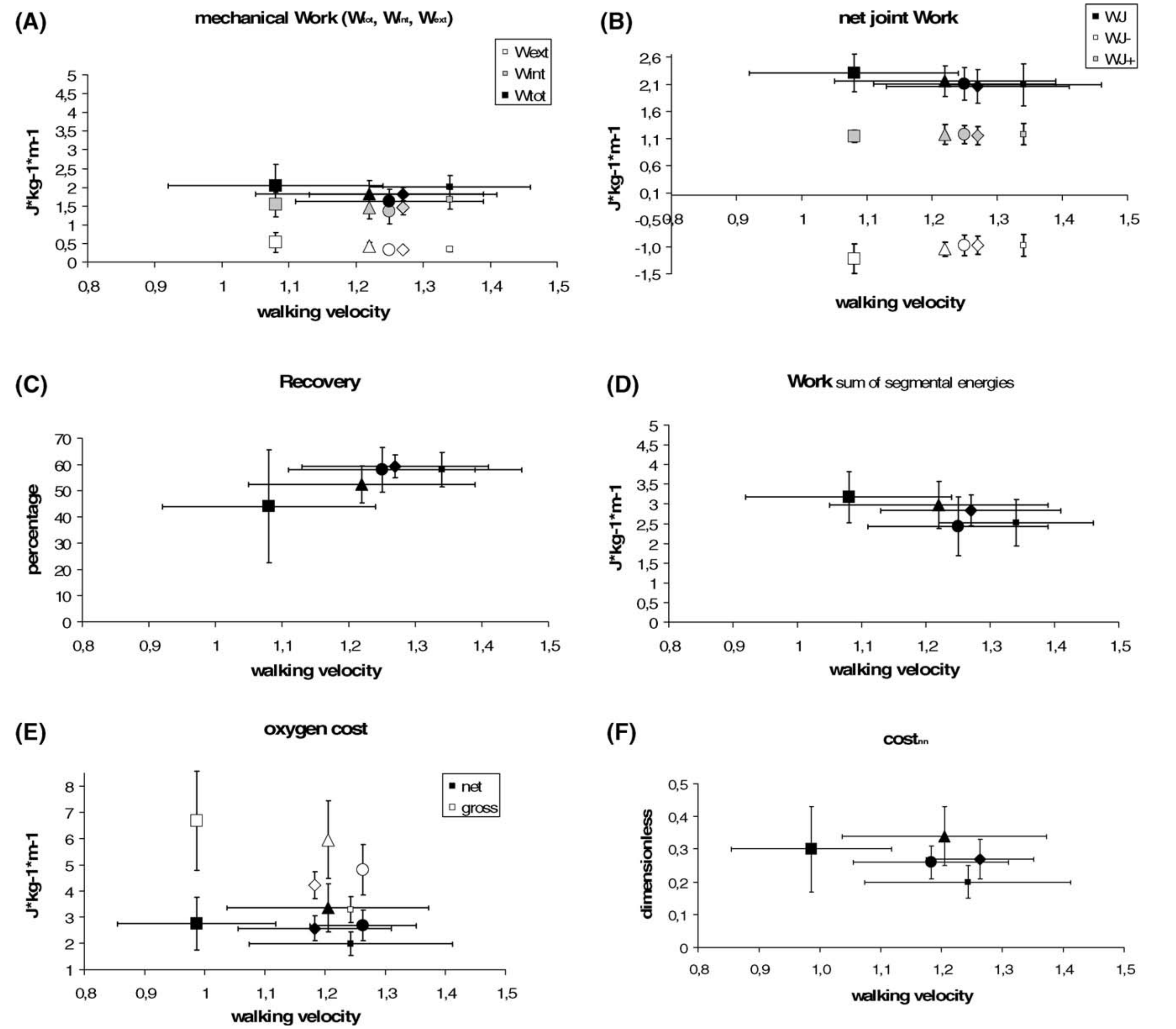


Fig. 1. Mean and standard deviation (vertical lines, when exceeding the symbol) per age group (G1, □; G2, △; G3, ○; G4, ◇; G5, ▫) of the different parameters of mechanical and metabolic energy expenditure plotted as a function of walking velocity. Horizontal bars represent standard deviation of self-selected walking speed. Note that WS_{SS} was different for mechanical estimations during gait analysis (GA) and during measurement of oxygen consumption ($r = 0.637$, $p < 0.001$). For GA WS_{SS} was lower for G1 compared to G2–5 ($p = 0.000$–0.019), and for G2 compared to G5 ($p = 0.048$). During measurement of O_2-consumption WS_{SS} was lower in G1 compared to G2–5 ($p = 0.000$–0.003).

differences between the groups were more related to the differences in WS_{SS}.

W_{SSE} consists of both positive and negative work performed to change E_{kin} and E_{pot} of the segments and can thus contribute to better understanding of why EE_{walk} is increased in children, but has not been previously reported. W_{SSE} continued to decrease until early adulthood. The fact that W_{SSE} is decreasing with increasing age and $W_{int,k}$ is not, suggests that positive work and negative work are not developing simultaneously. This is confirmed by the results of W_j, where no developmental trend could be found for W_j^+ while W_j^- decreased until 9 years. Negative work is mostly produced by bi-articular muscles, which are more difficult to control and it can be assumed that more time is needed to learn how to control them.

The decrease in E_{met} until adult age confirms the results of DeJaeger et al. who described a decrease in gross O_2-cost with increasing age [18]. Our results, however, could not confirm their findings that gross cost already reached adult values at 12 years of age. They are more in accordance with Waters et al. who still found significant differences between teenagers (13–19 years) and adults (20–69 years) [20].

Clear differences in development are seen between gross versus net O_2-cost (Fig. 2G). Gross cost is decreasing by increasing age in children (G1 – G3) and, although more gradual, is still decreasing in adolescents. This is in accordance with Schwartz et al. who found $cost_{nn}$ to be less sensitive to age changes than gross cost and attributed this partly to the decline in resting O_2-consumption with increasing age [22]. Careful study of our data shows indeed a decrease of resting O_2-consumption until 15 years of age. But even in net data, cost is decreasing with increasing age and a larger standard deviation is seen in the younger compared to the older age groups. This suggests that, in addition to changes in body dimensions, there is an ongoing maturation process between 3 years and adult ages. We can conclude that the use of net data is imperative for investigation and interpretation of

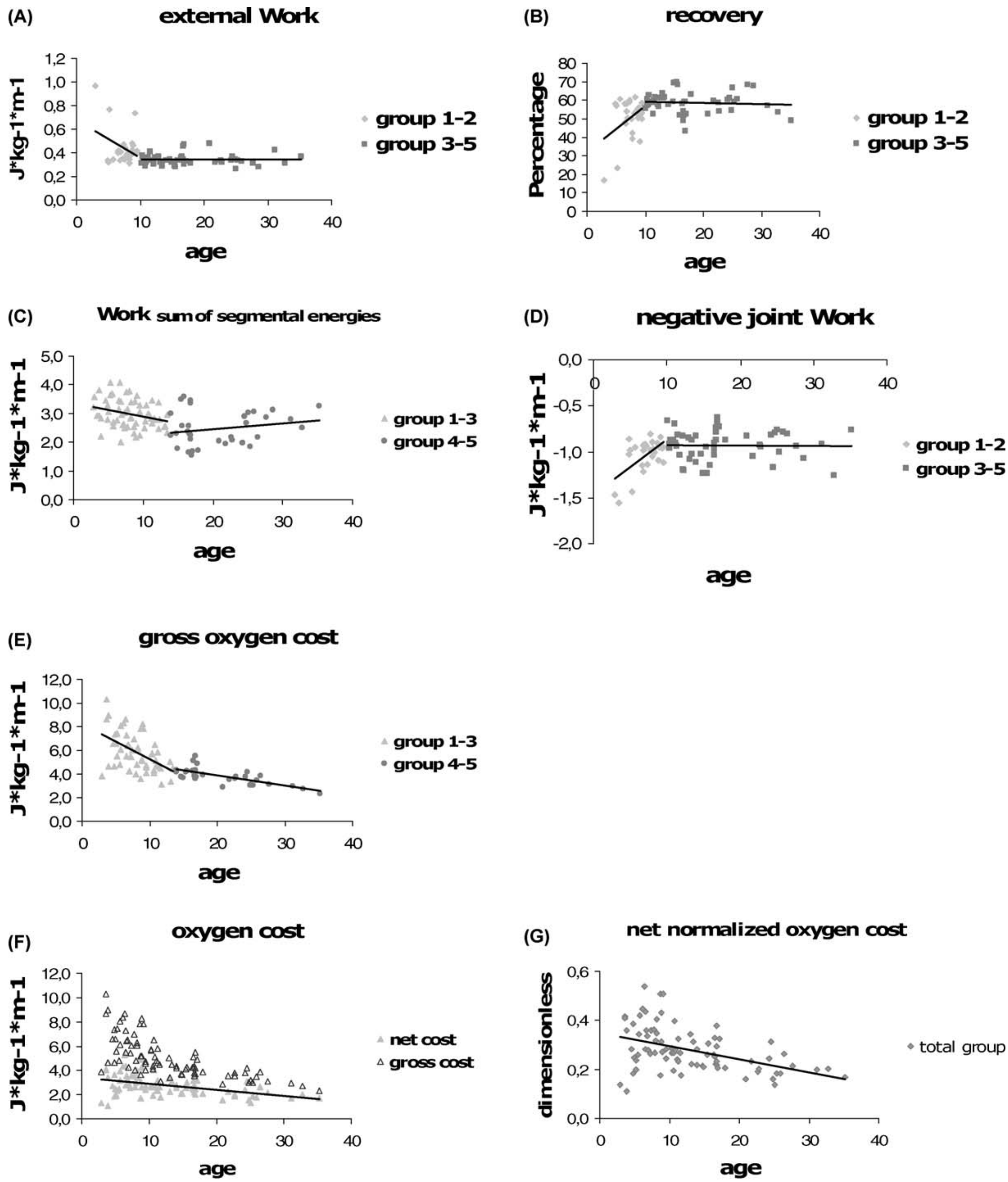


Fig. 2. (A–D) Regression analysis of immature and mature pool for energy parameters where General Linear Model (GLM) suggested development and regression line of the immature pool was (borderline) significant (<0.1). The intersection of both regression lines was considered as the estimated age of maturity. (E) Regression analysis of immature and mature pool for energy parameters where GLM suggested maturation and regression line of both immature and mature pool were significant (<0.05). Maturation continued (at a slower pace) in the mature pool. (F–G) Energy parameters with signs of maturation in GLM that could only be expressed in a regression of a single pool.

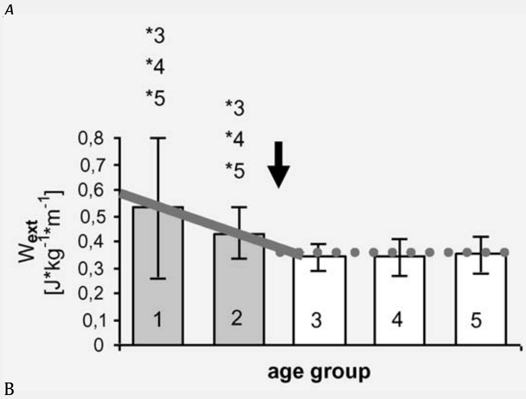
children's O_2-consumption, but even then age specific reference data should be used and a large variability between individuals should be taken into account.

An initial limitation of the study was that, due to technical restrictions, it was not possible to collect synchronized metabolic and mechanical data. Secondly, due to practical considerations GA was performed barefoot and O_2-consumption was measured while walking with normal shoes. Although walking with shoes alters stride length, kinematics and kinetics, there is no consensus if changes are clinically relevant [28,29]. We do not believe that the small differences between walking either barefoot or with shoes are of a nature that would influence the developmental trends in typical gait. Furthermore E_{met} was assessed over a steady state walking period and E_{mech} over three short walking trials resulting in differences in WS_{SS} between both tests. Simultaneous collection on a treadmill was not an option as data are meant to serve as a reference for pathological gait and an imposed speed on a treadmill may adversely affect gait pattern in patients. Another limitation is that E_{mech} and E_{met} were only assessed at WS_{ss}. From a clinical point of view it is most interesting to test at WS_{ss} but for E_{mech} and

Table 3

(A) Based on post hoc analysis an immature and mature pool was formed for linear regression analysis. The boundary between immature and mature pool was set when there was no longer a significant ($p < 0.05$) difference (*) between two adjacent age groups (arrow: group 3 is different from the lower but not from the higher age group and is thus part of the mature group). Regression in function of age was performed on the mean of all trials per subject within the immature (full grey line) and the mature pool (dotted grey line). (B) Variables for linear regression of immature (regression 1) and mature (regression 2) pool for energy parameters where General Linear Model (GLM) suggested development: x = independent variable = intersection of both regression lines when regression of the immature pool was significant and of the mature pool was not significant (estimated age of maturity). Significant regression of the mature pool in gross oxygen cost suggests that development continues although no significant difference was found between both age groups by GLM.

A



B

	Regression 1		Regression 2		x, age of maturity	Immature–mature pool [age group]	F; p-value
	Slope	Intercept	Slope	Intercept			
W_{ext}	−0.032^{o}	0.672**	5.67^{E}−05	0.341*	10.5 years	1–2 (N = 28) 3–5 (N = 50)	3.57; 0.069^{o} 0.00; 0.955
Recovery	2.451**	32.329*	−0.056	59.686**	10.9 years	1–2 (N = 28) 3–5 (N = 50)	4.26; 0.049* 0.22; 0.643
W_{SSE}	−0.051*	3.385**	0.020	2.057**	18.8 years	1–3 (N = 62) 4–5 (N = 35)	5.95; 0.018* 1,38; 0.248
W_j^-	0.061**	−1.475**	−0.004	−0.920*	9.0 years	1–2 (N = 29) 3–5 (N = 52)	14.78; 0.001 0.02; 0.900
Gross O_2-cost	0.001**	−17.250*	0.0002**	−2.167^{o}	–	1–3 (N = 52) 4–5 (N = 32)	8.46; 0.005* 22.29; <0.001*
Net O_2-cost	−0.051**	3.392**	–	–	–	1–5 (N = 83)	20.02; <0.001*
$Cost_{nn}$	−0.005**	0.348**	–	–	–	1–5 (N = 83)	20.28; <0.001*

W_{ext}, positive external work; W_{SSE}, work sum of segmental energies; W_j^-, negative joint work; gross O_2-cost [J], gross oxygen cost; N, number of subjects per pool used for analysis.

^{o} Significance level < 0.1.

* Significance level < 0.05.

** Significance level < 0.01.

the comparison to E_{mech} and E_{met} a speed range could help bring deeper insights. We also regret that we had an unequal number of trials between the groups. This was due to the fact that, for some subjects, we did not succeed in collecting three trials with valid kinetics. Not wanting to exclude valuable data, we choose to correct it statistically.

Both mechanical and metabolic EE_{walk} are still subject to development after the onset of walking. The results indicate that even in children without gait pathology different aspects of EE_{walk}, reflected by different mechanical and metabolic energy parameters, do not mature simultaneously. This stresses the need for age matched control data in the assessment of children with gait pathologies. Furthermore, it highlights the need to include both mechanical (including positive and negative work) and metabolic energy in the assessment of immature pathological gait in order to fully understand the nature and causes of their reduced efficiency.

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Conflict of interest statement

There are no financial and personal relationships of any of the authors listed below with other people or organisations that could inappropriately influence (bias) this work.

Appendix A. Positive external work and recovery

$$E_{pot}\,[J] = M_{tot} \times 9.81 \times CoM(z) \tag{A1}$$

$$E_{kin}\,[J] = \frac{1}{2} \times M_{tot} \times (v_x^2 + v_y^2 + v_z^2) \tag{A2}$$

$$R\,[\%] = \frac{(\Delta^+ E_{pot} + \Delta^+ E_{kin} - \Delta^+ E_{tot})}{(\Delta^+ E_{pot} + \Delta^+ E_{kin})} \tag{A3}$$

where $\Delta^+ E_{pot}$, ΔE_{kin} or ΔE_{tot} are the sum of the positive increments in E_{pot}, E_{kin} or E_{tot} over an integral number of steps.

Appendix B. Analysis of the energy changes of moving body segments (sum of segmental energies)

$$W_{\mathrm{SSE}}\,[\mathrm{J}] = \sum_{i=1}^{N} |\Delta E_{\mathrm{tot}}|$$

$$E_{\mathrm{tot}} = E_{\mathrm{pot}} + E_{\mathrm{kin}}$$

N, number of segments, in this case 12 (cfr. model $W_{\mathrm{int,k}}$) (according to Winter [30]).

Appendix C. Non-dimensional normalization scheme for oxygen utilization data

$$\mathrm{speed_{nn}} = v \times \left(\frac{1}{\sqrt{\mathrm{gLleg}}}\right)$$

$$O_2\ \mathrm{consumption_{nn}} = (O_2\ \mathrm{gross} - O_2\ \mathrm{rest}) \times \left(\frac{1}{\mathrm{mg}\sqrt{\mathrm{gLegL}}}\right)$$

$$O_2\ \mathrm{cost_{nn}} = \left(\frac{O_2\ \mathrm{gross} - O_2\ \mathrm{rest}}{v}\right) \times \left(\frac{1}{\mathrm{mg}}\right)$$

according to Schwartz et al. [22].

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